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# Modelling of localised gas preferential pathways in claystone

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ABSTRACT

A long-term injection gas test on initially saturated claystone samples under isotropic confining pressure is modelled in a 2D hydro-mechanical framework, which includes the hydraulic anisotropy. Evidences of localised pathways through the sample have been observed experimentally, which are difficult to reconcile with standard two-phase flow models. The presence of an embedded pre-existing fracture is included in a continuum finite element model. A hydro-mechanical coupling between the fracture aperture, permeability and the retention properties along the fracture is included in the model. Due to the increase in permeability and the decrease of the air entry pressure induced by the rise in fluid pressure at constant mean total stress, the model provides good agreement with the experimental observations. The discussion offers additional insight into the fluid flow mechanisms into the sample and the processes involved in the development of localised gas pathways. This study allows conclusions to be drawn regarding the performance of the model and its practical limitations.



## 1. Introduction

Argillaceous rocks are generally considered to be suitable geological barriers in radioactive waste disposal, as well as for $CO_2$ storage in deep formations. Their low permeabilities and retention capabilities offer interesting properties to limit the migration of the radionuclides released from the waste. In the field of radioactive waste confinement, the question of gas transfer in argillaceous formations is a crucial issue. Following repository closure, significant quantities of gases may be produced by the deterioration of the disposal components. It is important to understand the impact of gas production and migration on repository components, especially the clay barriers, in order to be able to predict the system behaviour with confidence over long time periods [1].

As suggested by Marshall et al. [2], different phenomenological processes can be defined to describe gas flows in low-permeability materials. When the gas production rates remain limited, diffusive transport of gas dissolved in pore-water may be adequate to prevent formation of a gas phase. However, if the rate of gas production exceeds the solubility limit of the interstitial fluid, a gaseous phase will be created. Under these conditions, gas will accumulate and visco-capillary flow may take place in the porous medium.

As gas pressures increase, complex behaviour for gas flow is generally observed. In laboratory studies performed on clay-based materials, gas flow is often associated with instabilities suggesting a dynamic network of conductive pathways. A common observation is that gas begins to flow once it has reached a given pressure (the breakthrough pressure), either when gas flow rate is controlled [3–7] or when gas pressure is imposed [3,8–10]. This behaviour is often interpreted as an indication of the opening of localised gas pathways inside the matrix [2].

Field investigations have been also performed to investigate the gas migration on clay host rock in various underground research laboratories [2,11–13]. While these observations can be difficult to analyse and compare with laboratory observations (because of the scale of the processes and uncertainties associated with characterisation of the boundary conditions), gas breakthrough phenomena have been observed [2,11]. These experiments have suggested that the test results are very sensitive to minor features, for example the presence of bedding joints or interfaces between materials.

Classic concepts of porous medium two-phase flow are inappropriate to model such gas flows [14,15]. Some contributions propose modelling tools to take into account the development of localised gas paths through the claystone. The lattice models views the porous medium as a series of capillary networks superimposed on each other with different radius and density [16–18]. Discrete fracture networks also provide a solution to represent the effective

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conductivity of fractured rock at a grid-block scale [19]. Porous medium models which include some form of heterogeneity associated with a number of intrinsic characteristics (permeability, porosity) also seem to provide a solution to explain such behaviour [20].

An alternative proposition dealing with equivalent continuum medium is to associate the development of advective gas pathways with gas migration through localised fractures predefined within the material. The effect of the presence of these discontinuities can be taken into account by coupling the aperture of the discontinuity and its equivalent permeability. The opening of the fracture can be induced by hydro-mechanical loadings (e.g. rise in fluid pressure, effective unloading of the rock). This hydro-mechanical coupling, referred to as an embedded fracture model, has been proposed by Olivella and Alonso [21] to explain gas flow mechanisms in plastic clays. Initially this model has been successfully applied in the modelling of laboratory gas injection tests under shear [21]. The embedded fracture model provides also a good representation of the gas permeability evolution along interfaces between two materials or along bedding joints as a response to stress and strain changes, at both the field scale [21,22] and the laboratory scale [6,22]. Collectively this work suggests that it is often necessary to consider small-scale spatially heterogeneities within the material when describing the initiation of gas flow.

To contribute to a better understanding of the processes associated with the development of localised gas pathways in claystone, the modelling of a long-term laboratory gas injection test using an embedded fracture model is studied. This experiment was performed by the British Geological Survey on Callovo-Oxfordian claystone (COx), the proposed host rock for the French radioactive waste repository [23,24]. The purpose of this test was to investigate the mechanisms governing gas migration in the COx. Results from this study indicate the movement of gas is through a localized network of pathways within the claystone whose properties vary temporarily and spatially within the claystone [7].

In this problem, the boundary conditions (i.e. isotropic confinement of the sample) do not allow the shear strength of the material to be reached and the development of the localised gas pathway is therefore not straightforward. It is proposed to consider the presence of a pre-existing fracture through the sample to better represent the development of these features. Moreover the experimental data acquisition of gas outflow under both increasing and decreasing gas pressures provides a framework to test the model under various hydraulic boundary conditions, which is rarely available.

This paper focuses mainly on the discussion of the numerical results and presents an in-depth analysis on the influence of the different components of the embedded fracture model. The different couplings are added progressively to the model in order to determine the significance of each in the reproduction of the gas breakthrough phenomena. This study highlights therefore the main effects that need to be taken into consideration for gas migration processes. The paper proposes additional insight into the model performance in simulating the gas flow processes in initially saturated claystone and allows modelling strategies to be drawn when describing practical problems of gas flow.

## 2. Long term laboratory gas injection test

To investigate the gas migration mechanisms in clay-rich media, the British Geological Survey has performed a number of long-term laboratory-scale tests on samples of Callovo-Oxfordian claystone (COx), a candidate host rock for the disposal of radioactive waste in France. Test specimens were manufactured by a combination of dry core-drilling (with gas flushing and vacuum removal of fines), diamond slicing and surface grinding, or produced by machine lathing, a more sympathetic process which is less likely to induce damage within the material as a result of sample preparation. In this experimental system, the sample is subjected to an isotropic confining stress with injection and backpressures controlled through high precision syringe pumps. The experimental set up uses a novel feature, i.e. the use of porous annular guard-ring filters around the inflow and outflow filters (Fig. 1). These allow the estimation of hydraulic anisotropy from a single test, as well as the monitoring of the pore pressure evolution in both guard-ring filters [25]. Testing is performed in an air-conditioned laboratory at a nominal temperature of 20 °C.

Prior to gas injection, each sample is first restressed with an isotropic confining pressure and a water pressure of 12.5 MPa and 4.5 MPa respectively. Confining pressure was applied in a series of steps in order to observe the consolidation response of the material. Once complete hydraulic testing was performed while the confining and backpressure were maintained constant. The water pressure at the injection filter was raised to 7.5 MPa and held constant until steady state conditions were observed. Once complete, the injection pressure was reduced back to 4.5 MPa ready for gas testing. The baseline hydraulic properties (intrinsic permeability and hydraulic anisotropy) may be determined during the hydraulic tests.

During the gas injection phase, helium injection occurs through the base of the sample by slowly increasing gas pressure in a series of steps (from 6.5 to 12 MPa) over a 600 days period and then by decreasing progressively the gas pressure (from 12 to 7 MPa). Finally, the injection pump was switched off and the gas pressure allowed decaying to define the apparent capillary threshold pressure. A backpressure of 4.5 MPa is continuously imposed on

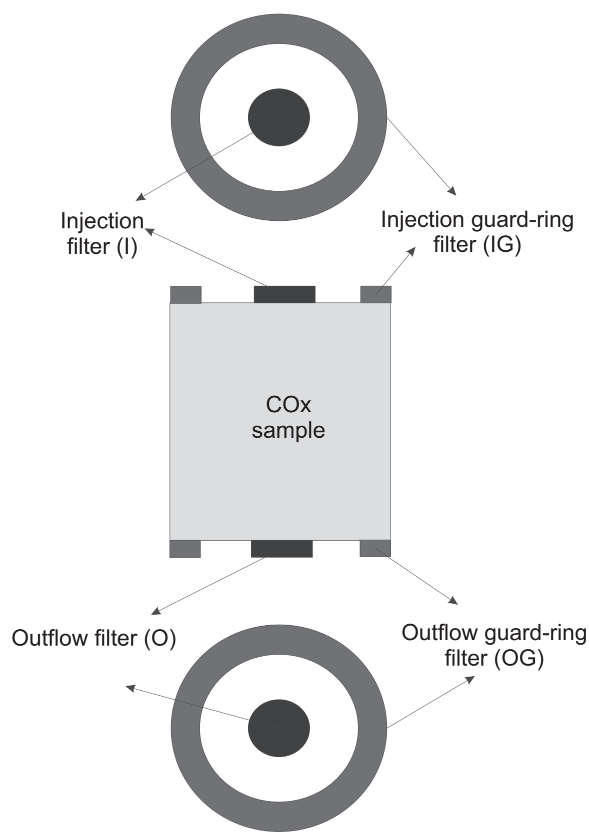


**Fig. 1.** Scheme of the experimental device.